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14. ABSTRACT
This report describes the results of studies of the response of the Earth's space plasma to high-power HF radio waves from the High-frequency Active Auroral Research Program (HAARP) facility in Alaska under the 2010-2012 AFOSR task `Physics of the Geospace Response to Powerful HF Radio Waves'. A first-principle model of a HF-created ionizing wave has been developed, quantitatively explaining the observed artificial plasma layers. The FLIP model has been adapted to the conditions of HF heating and explored to simulate artificial ducts. DMSP-HAARP experiments revealed that HF-created ion outflows and artificial density ducts in the topside ionosphere appeared faster than predicted by the models, pointing to kinetic (suprathermal) effects. CHAMP/GRACE-HAARP experiments presented the first evidence of F2-region atmospheric gravity waves generated by HF heating. A novel 3D numerical model of nonlinear interactions of lower hybrid waves with plasma particles has been explored. The resulting spectral energy distribution virtually reproduced the satellite observations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Evgeny Mishin
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Technical Summary:

1. The first theoretical model for HF-created descending artificial plasmas has been developed. Its basic idea is that enhanced ionization by suprathermal electrons accelerated by Langmuir turbulence near the critical altitude produces the artificial plasma sustaining interaction with the transmitted HF beam. The newly ionized plasma region moves toward the upward-propagating HF beam, thereby creating an ionizing wavefront. The basic assumptions of the model have been confirmed by exploring a multi-scale dynamic model for the creation and propagation of artificial plasmas. Ordinary mode electromagnetic waves excite parametric instabilities and strong Langmuir turbulence near the reflection point. The coupling between high frequency electromagnetic and Langmuir waves and low-frequency ion acoustic waves is numerically simulated using a generalized Zakharov equation. The acceleration of plasma electrons is described by a Fokker-Planck model with an effective diffusion coefficient constructed using the simulated Langmuir wave spectrum. The propagation of the accelerated electrons through the non-uniform ionosphere is simulated by a kinetic model accounting for elastic and inelastic collisions with neutrals. The resulting ionization of neutral gas increases the plasma density below the acceleration region, so that the pump wave is reflected at a lower altitude. This leads to a new turbulent layer at the lower altitude, resulting in a descending artificial ionized layer, which moves from near 230 km to about 150 km. At the terminal altitude, ionization, recombination, and ambipolar diffusion reach equilibrium, so the descent stops. The modeling results reproduce artificial ionospheric layers produced for similar sets of parameters during the high-power HF experiments at HAARP.

2. The FLIP and SAMI2 models have been adapted to the conditions of HF heating and used to simulate HF-created ion outflows, artificial density ducts, and descending artificial plasma layers. These models include only HF-induced electron heating near the critical layer. It has been shown that enhanced plasma transport and chemistry driven by the heating leads to the density depletion/enhancement above/below the nominal critical layer in the background ionosphere. However, the enhancement is too small to account for the observations of descending layers below 200 km, thereby confirming that HF-accelerated electrons are the main source of descending artificial plasmas.

3. Specially designed DMSP satellite-HAARP heating experiments have been conducted in 2010-2011 and revealed that artificial density ducts and ion outflows in the topside ionosphere appear more rapidly than the state-of-the-art two-fluid SAMI2 model predicted. This observation requires accounting for kinetic (suprathermal) effects absent in the conventional ionospheric models.

4. Under-dense noontime heating experiments at HAARP revealed that the electron density decreases/increases in time in the region below/above 140 km. This observation manifests the change of the balance between the photoionization, electron-ion recombination, and the electron-oxygen dissociative attachment losses caused by the heating. The latter is not included in the operational ionospheric models.

5. Nonlinear interactions of lower hybrid waves with plasma particles have been numerically simulated under the assumption of axially symmetric turbulence. This is the first nonlinear solution of the general form of nonlinear interactions of lower hybrid waves due to induced scattering, i.e., the so-called vector nonlinearity. The resulting spectral energy distribution strongly depends on the local lower hybrid resonance and resembles the in situ satellite observations. This simulation can also be applied to explore the lower hybrid acceleration mechanism in HF-ionosphere interactions near the upper hybrid layer.

6. High-power HF heating experiments have been conducted at HAARP in October 2008 and August 2011 in conjunction with the CHAMP and twin GRACE satellites carrying the STAR and SuperSTAR accelerometers, respectively. These experiments presented the first evidence of F2-region atmospheric gravity waves generated by HF heating. These results provide the groundwork for a new method of studying the ionosphere-thermosphere coupling.

7. HF heating experiments at frequencies f_0 near the 4^{th} electron gyroharmonic $4f_{ce}$ have been conducted at HAARP on 28 March 2011 between 1500 and 1600 AST to explore the development of artificial descending plasma

layers. Data come from concurrent measurements of the secondary radiation escaping the HF-pumped ionosphere, a.k.a. stimulated electromagnetic emissions (SEE), reflected probing signals at f0, and plasma line radar echoes from the MUIR radar. The artificial layers appeared only for injections along the magnetic field and $f_0 > 4f_{ce}$ at the nominal HF interaction altitude in the background ionosphere. Their average downward speed ~0.5 km/s holds until the terminal altitude where the local 4th gyroharmonic matches f_0. The total descent up to 30 km increases with the nominal offset f_0-$4f_{ce}$. The sensitivity to the sign of the offset f_0-$4f_{ce}$ indicates the important role of upper hybrid waves in the electron. However, the fact that in this experiment the descent starts during the first few pulses of period 2, i.e. faster than the striations and anomalous absorption at the UH level can develop, and the presence of enhanced descending plasma line echoes indicate also the significance of Langmuir turbulence. These observations suggest the coexistence of the O→UH and O→L instabilities and, possibly, UH→L wave coupling at the magnetic zenith.

Funding Summary by Cost Category

FY	In House	Capital Equip. (>5K each)	On –Site Contractor	Total
FY10	155,000	0	20,000	175,000
FY11	165,000	0	10,000	175,000
FY12	175,000	0	0,000	175,000

Appendix A: In-house Activities

Personnel:

FY2010	**Name**	**Degree**	**Discipline**	**Involvement**
Air Force Employees:	T. Pedersen	Ph.D.	Physicist	1/10
	C. Lin	Ph.D.	Physicist	1/7
On-site Contractors:	C. Roth	Ph.D.	Physicist	1/20
	W. Burke	Ph.D.	Physicist	1/20
Visitors:				

FY2011	**Name**	**Degree**	**Discipline**	**Involvement**
Air Force Employees:	T. Pedersen	Ph.D.	Physicist	1/10
	C. Lin	Ph.D.	Physicist	1/7
………………………	E. Sutton	Ph.D.	Physicist	1/10
On-site Contractors:	C. Roth	Ph.D.	Physicist	1/20
Visitors:				

FY2012	**Name**	**Degree**	**Discipline**	**Involvement**
Air Force Employees:	T. Pedersen	Ph.D.	Physicist	1/20
	C. Lin	Ph.D.	Physicist	1/10
………………………	E. Sutton	Ph.D.	Physicist	1/5
On-site Contractors:				
Visitors:				

Publications in Peer Reviewed Journals, Books, etc:

1. Milikh, G., E. Mishin, I. Galkin, A. Vartanyan, C. Roth, and B. Reinisch, Ion outflows and artificial ducts in the topside ionosphere at HAARP. *Geophys. Res. Lett*., *37*, L18102, doi:10.1029/2010GL044636, 2010.

2. Mishin, E., M. Starks, G. Ginet, and R. Quinn, Nonlinear VLF effects in the topside ionosphere. *Geophys. Res. Lett.*, *37*, L04101, 10.1029/2009GL042010, 2010.

3. Mishin, E. and T. Pedersen, Ionizing wave via high-power HF acceleration, *Geophys. Res. Lett.*, *38*, L01105, doi:10.1029/2010GL046045, 2011.

4. Galinsky, V., V. Shevchenko, E. Mishin, and M. Starks, Numerical modeling of 3D weak turbulence driven by high-power VLF pump waves in the topside ionosphere, *Geophys. Res. Lett*., *38*, L16105, doi:10.1029/2011GL048441, 2011.

5. Kuo, S., A. Snyder, E. Mishin, P. Kossey, and J. Battis, Ionospheric modification from underdense heating by high-power HF transmitter, *J. Geophys. Res.*, *116*, A03304, doi:10.1029/2010JA016244, 2011.

6. Mishin, E., E. Sutton, G. Milikh, I. Galkin, C. Roth, and M. Förster, F2-region atmospheric gravity waves due to high-power HF heating and subauroral polarization streams, *Geophys. Res. Lett*., *39*, L11101, doi:10.1029/2012GL052004, 2012.

7. Milikh, G., A. Demekhov, A. Vartanyan, E. Mishin, and J. Huba, A new model for formation of artificial ducts due to ionospheric HF-heating, *Geophys. Res. Lett*. 39, L10102, 10.1029/2012GL051718, 2012.

8. Vartanyan, A., G. Milikh, E. Mishin, M. Parrot, I. Galkin, B. Reinisch, J. Huba, G. Joyce, and K. Papadopoulos, Artificial ducts caused by HF heating of the ionosphere by HAARP, *J. Geophys. Res.*, *117*, A10307, doi:10.1029/2012JA017563, 2012.

Accepted/Submitted for Publication:

1. Eliasson, B., X. Shao, G. Milikh, E. Mishin, and K. Papadopoulos, Numerical modeling of artificial ionospheric layers driven by high-power HF-heating, *J. Geophys. Res*., 2012 (in press).

2. Sergeev, E., S. Grach, A. Shindin, E. Mishin, P. Bernhardt, S. Briczinski, B. Isham, M. Broughton, J. LaBelle, and B. Watkins, Artificial Ionospheric Layers during Frequency Stepping near the 4th Gyroharmonic, *Phys. Rev. Lett*., 2012 (under review).

Invited Lectures, Presentations, Talks, etc:

1. Huang, C., C. Lin, E. Mishin, and T. Pedersen, Investigating COSMIC GPS radio occultation observables as diagnostics for ionospheric HF heating experiments, 4th FORMOSAT-3/COSMIC data users' workshop, 27-29 October 2009, Boulder, CO.

2. Mishin, E., and T. Pedersen, Electron acceleration and ionization production in high-power heating experiments at HAARP, USNC-URSI National Radio Science Meeting, 6-9 January 2010, Boulder, CO.

3. Mishin, E., Effects of high-power high frequency radio waves on geospace, Boston University Center for Space Physics, 18 March 2010, Boston, MA.

4. Mishin, E., Nonlinear plasma effects in natural and HF-perturbed subauroral ionosphere, 52nd Annual Meeting of the APS Division of Plasma Physics, 8-12 November 2010, Chicago, IL.

5. Mishin, E., Sensing plasma upflows during HF heating, GIRO Forum, 10-15 May 2011, Lowell, MA.

6. Mishin, E. and G. Milikh, HF-induced density ducts and ion outflows in the topside ionosphere, 17th RF Ionospheric Interactions Workshop, 17-20 April 2011, Santa Fe, NM.

7. Mishin, E. Absorption of electromagnetic waves in the ionosphere, 17th RF Ionospheric Interactions Workshop, 17-20 April 2011, Santa Fe, NM.

8. Mishin, E. and T. Pedersen, Electron acceleration and ionization production in high-power heating experiments at HAARP, XXXth URSI General Assembly, 15-20 August 2011, Istanbul, Turkey.

9. Mishin, E., C. Lin, and T. Pedersen, Physics of the Geospace response to powerful HF radio waves, AFOSR Space Science Program Review, 23-24 June 2011, Albuquerque, NM.

10. Sergeev, E., S. Grach, A. Shindin, E. Mishin, P. Bernhardt, S. Briczinski, B. Isham, M. Broughton, J. LaBelle, and B. Watkins, Artificial Ionospheric Layers during Frequency Stepping near the 4th Gyroharmonic, Artificial ionospheric layers during frequency stepping near the 4th Gyroharmonic, 39th COSPAR Scientific Assembly,14-22 July 2012, Mysore, India..

“Professional activities” and awards

1. E. Mishin convened and co-chaired the workshop "Nonlinear Plasma Effects in Auroral/Subauroral Plasmas” at the 2010 CEDAR Workshop, Mini-conference "Nonlinear Plasma Effects in Geospace Plasma” at the 53rd/54th Annual Meetings of the APS Division of Plasma Physics in 2011/2012, and Session “Multi-scale Magnetosphere-Ionosphere Interactions” at the 2012 AGU-AOGS Joint Assembly.

2. E. Mishin has been awarded the 2010 Space Vehicles Directorate Senior Scientific/Technical Achievement award.

3. E. Mishin has been elected a Fellow of the American Physical Society in 2011.

4. E. Mishin and T. Pedersen served on the DARPA panel on the Instant Fire Suppression and BRIOCHE programs in 2010-2012.

5. E. Mishin has been awarded the 2012 G. Loeser Award.